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Dynamic behavior of a multi-wavelength acousto-optic filter

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Abstract

Wavelength tunable filtering in optical telecommunications can be done by taking advantages of the acousto-optic interaction in anisotropic medium and especially with a quasi-collinear interaction in paratellurite crystal. The objective of the paper is to point out the limit of the functioning of such a component, in the case of a multi-wavelength filter application. The dynamic behavior (i.e. the temporal evolution) of the optical diffraction efficiency according to the operating conditions is presented and discussed. Experimental and simulation results, in telecommunication wavelength range, are shown.

Keywords: Acousto-optic, quasi-collinear interaction, tunable filter, frequency beating, multi-wavelength filter

1. Introduction

Wavelength Division Multiplexing (WDM) has become the standard technology in fiber data transmission. For optical implementation of WDM networks, the development of reconfigurable optical devices is required, like tunable optical filter. One solution to achieve this key device is based on the use of acousto-optic interaction in anisotropic medium. The diffraction of light by an acoustic wave propagating in the interaction medium is the basic principle used in the design of a tunable acousto-optic filter (AOTF). The acoustic wave, generated by a RF signal applied to a piezoelectric transducer bonded on the medium, produces a periodic change in the refractive index thanks to the photo-elastic effect. Then, the medium acting as a diffraction grating, an incident optical beam can be diffracted through it. The RF frequency controls the transmitted (filtered) wavelength and the RF amplitude level allows to adjust the filtered light intensity level. The main advantage of this technique is a complete absence of any moving part which leads to a reliable, stable and fast technique for wavelength tuning.

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In the following, we are particularly interested in quasi-collinear interaction where acoustic and optic beam both follows the same path all along their interaction zone (V. Molchanov et al (2009)). This type of interaction offers narrow wavelength resolution with good out of band wavelength rejection and low drive power requirements.

Simultaneous selection of multiple wavelengths can be performed by applying multiple RF signals to the transducer with different frequencies. The multi-wavelength filter operation requires the superimposition in the crystal of several acoustic sinusoidal waves. In those case, beat frequencies appears when the acoustic wave frequencies are close. In this paper we are particularly interested in the influence of those beat frequencies on the diffraction efficiency changes over time. We propose to show the filter's effects induced by these acoustic beats. The results presented in this paper concern the superimposition of two RF signals. In section 2, we present the acousto-optic cell structure used for this study. The section 3 is devoted to the theoretical and experimental results for a two-wavelength filtering. Finally, comments on filtering application with quasi-collinear acousto-optic cell are given.

2. Quasi-collinear acousto-optic tunable filter

The filter used in our application is made with a bulk tellurium dioxide crystal (TeO_2). The filtered optical wavelength bandwidth for this device is 1100-2200nm for RF signal frequencies from 26 to 54MHz. The construction of the filter is shown schematically in Fig. 1.a.

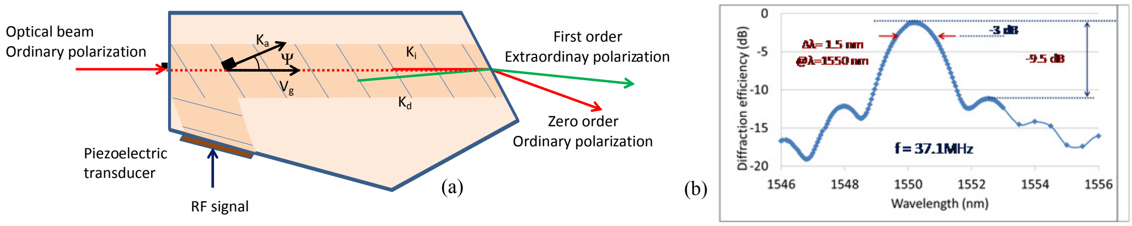

Fig. 1: (a) AOTF architecture; (b) Diffraction efficiency as a function of wavelength for white light source, tuned for 1550nm.

When a RF signal is applied, the transducer emits an acoustic wave which is reflected from the input optical face of the crystal. The angle between the incident optical beam and the normal of the optical crystal face is equal to 0°. Then, the optical beam interacts with the acoustic wave transmitted in shear-mode. The AO interaction takes place over about 2cm length and the interaction time of this filter is approximately 25µs. This AOTF architecture is designed in order to obtain quasi-collinear interaction (close-to-collinear configuration), i.e. the acoustic wave group velocity is collinear with the optical incident beam. Note that the wave vectors of the incident and diffracted optical beams are differently oriented, thus allowing an angular separation between them at the crystal output.

Figure 1.b presents the AOTF normalized transmission response as a function of the wavelength for a fixed RF frequency. The AO cell is illuminated with a white laser source. All the characterizations are performed with an optical beam ordinary polarized with a diameter of 1.2mm and a RF signal power of 125mW. The diffracted beam is coupled through a focuser in a single mode fiber and is measured with an Optical Spectrum Analyzer (OSA). Result is presented for a RF frequency equal to 37.108MHz, which allows the selection of the 1550nm wavelength. Measurements of the diffraction efficiency shape for different selected wavelengths over the 1500nm-1600nm range show that the maximum diffraction efficiency is around 75%, the FWHM (Full Width at Half Maximum) around 1.5nm and the minimum gap between side lobes and the main peak (SFDR: Spurious-Free Dynamic Range) around 10dB, as presented in Issa et al (2014).

3. Multi-wavelength AOTF

AOTF are also suitable for multi-wavelength optical cross-connects for reconfigurable network architectures that can adapt to changing traffic patterns. Then, by applying several RF signals with different frequencies, the AOTF can simultaneously filter out several wavelengths. However, when two or more acoustic signals propagate simultaneously in the crystal, beat acoustic frequencies appears. In the case of close acoustic frequencies, the interaction area may be affected by this beating and then the diffracted optical signal may be modified. We show experimentally, that when two close wavelengths are selected, the diffracted optical beam is disturbed: temporal fluctuations on the optical intensity appear. Those intensity fluctuations may be critical for the development of telecommunication systems, so they must be analyzed and controlled.

3.1. Time-frequency model

We suggest a time-frequency analyze of the acoustic signal to get information upon the diffracted optical intensity evolution. We propose a model based on the fact that the optical diffracted intensity depends on both amplitude and frequency distribution of the acoustic field in the interaction area. We used the Fourier transform to calculate the power spectral density. Its spreading depends on the interaction length. So, we consider that the diffracted intensity for a selected wavelength is proportional to the acoustic power spectral density calculated for the corresponding frequency over the T_L duration. The equation 1 gives the acoustic instantaneous power density.

$$P_s(f,t) \propto |S(f)|^2 = \left|\int_0^{T_L} s(t)\, e^{-j2\pi f t}\, dt\right|^2 \tag{1}$$

with s(t) the acoustic signal, f the acoustic frequency equal to the RF one and T_L the interaction time corresponding to the interaction length divided by the acoustic velocity.

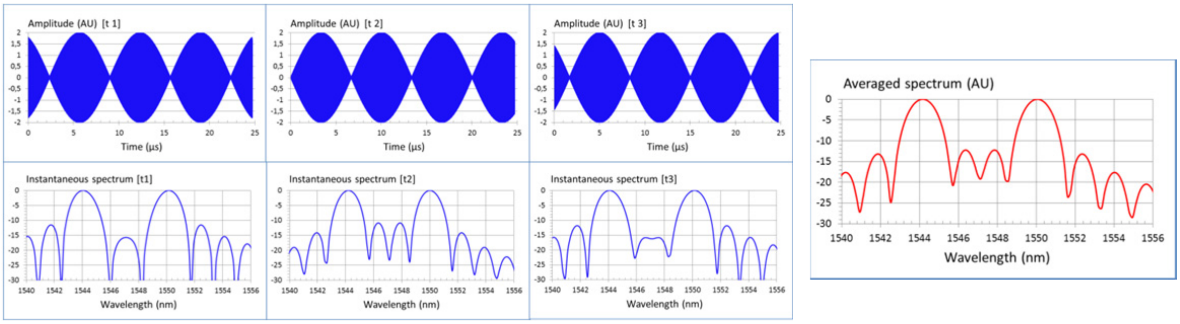

Fig 2: Temporal acoustic signal and instantaneous power density associated for three times points: t_1, t_2 and t_3 and averaged power density.

In the case of two acoustic signals applied simultaneously in the crystal, figure 2 presents both, the truncated acoustic signal due to the interaction length and the instantaneous power density associated. They are presented for three different times. Those curves clearly show that the diffraction grating, resulting from the superposition of the two waves, changes as a function of the time over the interaction area. It is due to the frequency drift between the two acoustic signals. In order to compare the simulation results with measurements made with an Optical Analyzer Spectrum (OSA), the Ps(f,t) must be averaged over a T_{max} duration, with $T_{max} >> T_L$. Figure 2 presents this spectral average. We find a good agreement between measurements and simulations.

3.2. Theoretical and experimental results

It is important to analyze the beating impact over the temporal evolution of the optical beam intensity. We study here the diffraction efficiency as a function of the difference Δf between the acoustic frequencies when two RF signals with frequencies f_1 and f_2 are applied to the transducer. Fig. 3 presents two 3D charts for two cases. In the case a (Δf = 150kHz), we can clearly see than the selection of the two wavelengths is correctly down even if we notice a weak temporal evolution of the optical intensity. In the case b (Δf = 20kHz), where the selected wavelength difference is slightly lower than the AOTF bandwidth, the temporal evolution cannot longer be neglected.

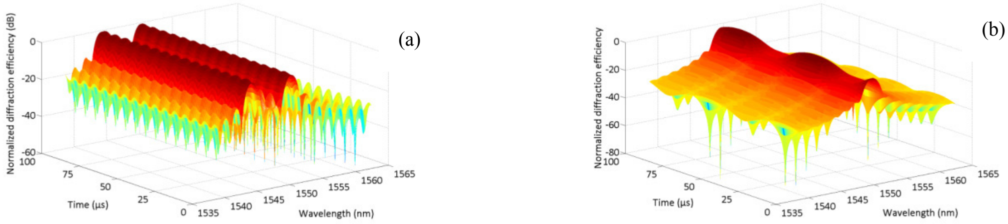

Fig. 3: (a) f_1 = 37.108MHz and f_2 = 37.258MHz (Δf = 150kHz); (b) f_1 = 37.108MHz et f_2 = 37.128MHz (Δf = 20kHz).

We have studied this temporal evolution as a function of the difference Δf between the two acoustic frequencies. The result is presented in figure 4, where the variation is defined as the ratio between the amplitude and the averaged values of the diffracted optical signal. We present both the case of the variation of the total intensity (a) and the case of the intensity integrated around 1550nm over 1.5nm (b).

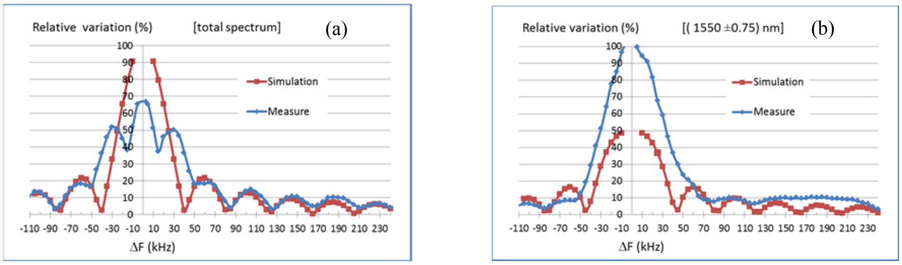

Fig. 4: Simulation and measurement of the optical intensity variation as a function of the difference Δf between the two acoustic frequencies.
(a) Intensity averaged over the entire wavelength range; (b) Intensity averaged around 1550nm over 1.5nm

We notice that the optical intensity varies periodically as a function of Δf. A good agreement is observed between the simulation and the measurement behaviors, except for Δf around or less than 40kHz. Those temporal fluctuations can be critical for system functioning. For example, in the case of a system based on an AOTF filter requiring temporal intensity variations less than 10%, then acoustic frequencies must be separated at least by 70kHz which includes a separation more than 2.8nm between selected wavelengths.

4. Conclusion and perspectives

The aim of this paper is to point out the temporal fluctuations of the optical intensity which can be critical for some applications and especially for telecommunication systems. Indeed, the multi-wavelength filtering can generate intensity fluctuations due to the frequency beating between the acoustic signals. Those fluctuations are all the more important as the acoustic signal frequencies are close.

We have proposed a time-frequency analyze of the acoustic signal. Simulations and measurements have been compared. This first approach gives some interesting results particularly for distant frequencies. In contrary, the model is not accurate enough when the frequencies are close. Next works will concern the improvement of the model by taking into account some neglected physical phenomena (as acoustic and optical divergence, acoustic attenuation …). The proposed model is unidimensional: the spatial dimension considering the acoustic phase repartition over the optical beam area needs also to be regarded.

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